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# DEVELOPMENT OF A STRETCHABLE CONCAVE IMAGING MEMBRANE MIRROR OF VARIABLE FOCUS

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The report describes the evolution of a plastic membrane, variable focus, concave imaging mirror, a 'zoom' mirror. A partial vacuum behind the membrane is used to create a uniform pressure difference across the membrane and force it back into a concave shape. Range of curvatures (obtainable) is from the flat to F/0.5, the classical limit for imaging in concave mirrors. Plastic membranes have been metallised with surface roughnesses down to 10 angstroms, as good as any mirror polished to date. Shearing interferometry has been used to study mirror symmetry. Frames are being evolved to support the membrane in such a way that the mirrors will be interferometrically symmetrical and capable of excellent imaging. Plastic membranes can be obtained to 17 metres wide, enabling mirrors to around 50 feet in diameter to be built and capable of optical imaging. A space mirror has been built, capable of operation even in a total vacuum. The mirrors are vacuum sealed and can retain any one curvature for long periods of time. The mirrors have been used with gas lasers to create very large sized holograms and white light holograms.

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## 1. SUMMARY

In 1983 the writer produced a stretchable, aluminised plastic membrane, circular concave imaging mirror. The unit was capable of variable curvature, each curvature having an associated focal length. Full details of this and improved units are to be obtained from a recent PhD thesis, November 1987, reference (1). The reflected, focussed images from the 1983 unit were extremely poor, for reasons given later in this report. The mirror was only used as a large diameter light collimating system of twenty four inches aperture, in a moire'-Schlieren flow visualisation system, reference (2). The mirror was substantially improved throughout 1983/84, good reflected focussed images were obtained, believed to be a first, references (3) and (4). In August 1985 a twenty six inch aperture mirror was built and displayed at the British Association AGM meeting, University of Strathclyde. The unit was reported on the front page of the London Times , the Edinburgh Scotsman and slightly later in Spectrum, references (5), (6) and (7). In December 1985 details were released of the vibration response of the membrane mirrors, reference (8). In May 1986 mirrors were delivered to T.R.W., Los Angeles (Directed Energy laboratory) and the British Royal Navy. T.R.W. stated response was that the writer had made a large contribution to active optics imaging techniques.

In the summer of 1986, U.S.A.F. personnel (Dr La Rell K. Smith, E.O.A.R.D., London; and Dr A. Guenther, Chief Scientist, Kirtland Air Force Base, Albaquerque) inspected the mirrors in Glasgow. The writer was invited to display the mirror to U.S.A.F. personnel in America. A mirror was displayed in late September 1986 at Kirtland and Hanscom A.F.B. The writer was accompanied by T.R.W. personnel who displayed their supplied flexible mirror test results, working the mirror to diffraction limited efficiency, using associated phase conjugate optics. A remarkable piece of research. Much enthusiasm was generated by the visit, culminating in the award of a U.S.A.F. one year pilot contract, June 1st 1987 to June 1st 1988, to maintain the impetus of the Strathclyde research.

In November 1987 details were published on the use of a flexible mirror combined with an image derotator to visualise the radiated heat patterns from high speed rotating components, references (9), (10) and (11). Details were also released on the use of the flexible mirrors to create very large white light holograms, reference (12), believed to be a first. The same technology could be used to create lightweight hologram mirrors, in which holograms actually replace the mirror, reference (13). Such technology is used in head up displays and has known S.D.I. uses.

Details will be given of the design and use of a lateral shearing interferometer, capable of examining all

mirror curvatures and apertures, in order to check for symmetry of curvature, plastic faults, aluminising faults on the plastic etc. The shearing interferometer has proved to be invaluable. Details will be given of the various plastics and aluminising techniques used in the report period. Details will also be given of a special mirror created for this report, which can be operated anywhere, even in space. In the year June 1987-1988 large improvements have been made in mirror construction, mainly due to the shearing interferometer examination of the evolved mirrors.

## 2. INTRODUCTION

### a) STRATHCLYDE UNIVERSITY FLEXIBLE CONCAVE MIRRORS

The mirrors to date have used thin, flat, constant thickness, metallised plastic sheets, typically 1 to 5 thousandths of an inch thick (25 to 125 micron), the sheets have been either rolled or cast. From experience it is found that as the rolled sheets get thinner, there is less control on the thickness variations. The rollers can exhibit vibration and or general movement which results in substantial thickness variations. The sheets can be metallised with mirror finishes by the sheet manufacturer or sent to specialised metallisers, depending on what is required by the customer. Rollers do not have an optically smooth finish, therefore roller surface marks can appear on the surfaces of the rolled sheets. Obviously such marks will lead to target light being scattered by the marks, leading to a degree of loss of image resolution. Good quality rolled metallised sheets can have smoothness values of around 30 to 40 Angstroms, as good as the finish of an average telescope mirror. Sheets wider than the axial length of the rollers can be produced by gripping the soft rolled sheet and stretching that sheet orthogonally to the rolled direction. Such a sheet is known as a biaxially stretched sheet, strain is locked into the sheet in orthogonal directions. Such sheets possess a phenomenon, that of rapid shrinkage with application of heat. The phenomenon varies from plastic to plastic, the mechanism is highly anisotropic, in some cases there can be shrinkage along one axis and expansion along the other. The amount of shrinkage depends on the previous history of the material, is time dependent and a function of temperature and humidity. High temperatures and humidities will greatly accelerate the shrinkage. Heat treatment, annealing, can be done on the uncoated sheets. Best results achieved by the writer to date have been obtained under light in plane tension to prevent warping.

Use can also be made of cast plastic sheets. The sheets are cast on extremely smooth surfaces, float glass, liquids etc. Roughness to around 10 Angstroms R.M.S can be obtained commercially. Cast widths at present are limited to around 2 metres, but manufacturers admit they could go to enormous widths if a market existed. Rolled plastic sheet widths to seventeen metres are known, enabling mirrors to be constructed up to 50 feet in diameter. The cast plastic sheets have problems. The material properties can vary from point to point on any one small sheet, causing variable stretch and variable curvature or bulging on the concave mirrors, a bad feature. Rolled sheets are preferred at the time of writing this report.

The Strathclyde mirrors use a circular disc of metallised mirror finish plastic, uniformly thick and stretched over a specially shaped circular frame. Vacuum is applied to the rear central area of the disc, air pressure difference now forces the mirror back into a concave shape. Variation of the vacuum alters the pressure difference and hence the mirror curvature is changed. The mirrors are vacuum sealed and can be held at any one curvature for long periods of time.

Theoretically it can be shown that for a circular, flat, uniformly thick plastic membrane, uniformly gripped at the circumference and evenly tensioned under a uniform pressure difference across the surface, that with <u>no</u> backing frame and being deformed into a concave shape, reference (1).

$$\Delta P = \frac{Ehb^3}{a^4}$$

where E, is Youngs modulus
h, is membrane thickness
b, central deflection
a, mirror circumferential radius

For a plastic membrane, $\Delta P = \dfrac{3.53Ehb^3}{a^4}$

The influence of the specially shaped circular stretching frame is small, experiment shows that,

$$\Delta P = \frac{3.46Ehb^3}{a^4}$$, reference (1).

From the equation it can be seen that the pressure difference increases dramatically as the mirror radius or diameter is reduced and the central deflection is increased i.e. small sized deeply curved mirrors.

If attempts are made to make small sized deep curvature mirrors with say 25 micron thick rolled plastics, the large pressure differences causes the large thickness variations of the ultra thin plastic to locally bulge, scattering light and dramatically reducing image resolution. It has been found preferable for a variety of reasons to use at least 125 micron thick metallised plastic sheets. Using such sheets and partial vacuum conditions one can easily achieve a large range of curvatures from the flat to an f/no of 0.5, the classical limit for image resolution. An f/no is the mirror focal length divided by the mirror aperture used. One can change the f/no by stopping down from the mirror circumference, or full aperture, and use an ever smaller central area of the mirror for one fixed focal length. Or one can use the full aperture and change the focal length, or stop down and also change the focal length. If really thick plastic, or metal diaphragm sheets are used, a partial vacuum at the rear is not enough. The sheets would now have to be pressurised back from the front, using pressures greater than $P_{atmos}$, with also possibly partial vacuums at the rear of the sheet. Such techniques have been explored by the writer in a special mirror, described later.

It can be shown for a lightly tensioned, edge gripped, circular, flat surface, that the maximum strain at the greatest curvature required of f/0.5 is approximately 4.7%, irrespective of the mirror diameter, reference (1). Since most rolled plastics have a yield strain of 5-7% (Mylar etc.) it can be seen that the mirrors are not strained beyond their elastic limit. Such mirrors will spring back to the flat position on release of the vacuum. For the mirrors described the maximum resultant stresses and strains occur at the centre of the mirror, the resultant stresses reducing dramatically along any radius towards the edge of the mirror. The presence of the central stretching frame over which the material is tensioned serves three purposes. It provides a simple vacuum seal, smooths out non symmetries of tension and can if required thin down the plastic passing over the frame top, by using large pull down forces to flatten out the plastic sheet. On application of vacuum to the rear of the mirror the material now takes up a different stress and strain relationship than would have been the case if the material had not been thinned in passing over the frame. Such stress and strain control at the boundary of the mirror (the frame top) can alter the actual curvatures of the mirror. With cast plastics, yield strains of 15 to 20% are available, enabling either f/nos to less than f/0.5 to be obtained, or reduce the plastic creep to an absolute minimum for any f/no down to f/0.5. If attempts are made to thin the plastic at the frame top then the tension must be very uniform and symmetrical around that top, otherwise the plastic in thinning will simply magnify any tension or strain differences. The end result is a very non symmetrical mirror of poor imaging quality. Having discussed generalisations, specific designs can now be discussed, leading to the designs utilised in this report.

b) <u>ORCHESTRAL DRUM MIRROR</u>

Reference (2) describes a mirror made using an old drum. The drumskin was removed and replaced with 15 micron thick metallised plastic foil, the foil was wrapped around the drumskin ring. The ring is pulled down over the thin circular end of the drum casing by axial tensioning bolts, thus tensioning the plastic and creating an initially flat surface. Vacuum in the drum body now created a concave plastic mirror. Images were extremely poor because the drumskin ring was not accurately circular, the drum casing was not circular or symmetrically stiff, it bulged non symmetrically under a pressure difference. The unit was not vacuum sealed and the foil vibrated with pulsations from the vacuum pump.

c) <u>CIRCULAR STRETCHING FRAME, FRICTION EDGE GRIPPED MEMBRANE</u>

Figure 1, from reference (7), illustrates the metallised membrane, friction gripped between two bolted flat thin circular rings (A). No pretensioning of the film was attempted directly in the rings. The rings were now pulled down by bolts over a concentric, circular, radially broad central stretching frame (B). The frame smooths out non symmetries of tension in the film and provides an excellent vacuum seal for only light contact forces between the film and the frame. The frame top must not have any sharp edges or even severe changes of curvature, the sharp edges bite into the membrane and cause localised stess and strain concentrations. Unless these concentrations are symmetrical around the frame top, a non symmetrical mirror is created with poor imaging.

A vacuum is introduced inside the stretching frame, in order to create a concave mirror. A soap bubble is a membrane and assumes a spherical shape because the resultant stresses are everywhere equal. In general the flexible concave imaging mirrors do not have equal resultant stresses along any one radius, hence the shape cannot be spherical, unless one is using very shallow curvatures. In general the shape is aspherical, the specific shapes and equations are listed in reference (1). Providing the shape is a symmetrical aspheric, then image aberrations such as spherical aberration, can be corrected as discussed later. If the produced shape is not symmetrical then the aberrations can not be cancelled. The most common solid, polished mirror curvature shapes used in imaging are parabolic, spherical and elliptical. The parabolic concave mirror perfectly focusses and images on axis, an on axis object at infinity (a star). The light from such distant objects is perfectly collimated. If the object is not at infinity then spherical aberration occurs, the target light is not collimated and is imaged on axis in many axial planes which overlap and blur the image. If the object is also off axis, i.e. lying off a line through the mirror centre and normal to the mirror surface, i.e the mirror optical axis, then coma occurs. The image points are imaged off axis and are drawn out like a comet tail, the image blurs. Spherical aberration is proportional to the reciprocal of the f/no cubed, coma is proportional to the reciprocal of the f/no squared. Coma and spherical aberration are easily produced by examining large objects close to the mirror, the majority of the object points are off axis by a large degree, the image points are also off axis and are coma blurred. If the object is on axis but not at infinity use can be made of a specific shaped elliptical mirror to focus and image on axis, a perfect aberration free image of the object. Again if the object is off axis or the wrong curvature of elliptical mirror is used then spherical aberration and coma occur and blur the image. Should a spherical mirror be used, this is the cheapest and easiest type to manufacture, then for very distant on axis targets the collimated target light is badly affected by mirror spherical aberration. Off axis target images are affected by coma. The Schmidt telescope achieves a wide field of view, that is the ability to image off axis targets, by using transmissive and reflective corrector plates to bend the target light before reaching the main focussing imaging mirror. Such systems control the main aberrations to designed degrees. In the conclusions of this report mention will be made of other aberration controls which can be used with the flexible mirrors. The Strathclyde flexible mirror shapes can be controlled by placing contoured flexible sheets behind the membrane, reference (4). Specific radial contours can be moulded in thick backing sheets, the radial variable thickness of the sheet now controls the membrane to give spherical, parabolic, or elliptical shapes. It is doubtful if one can produce accurate variable thickness ultra thin metallised plastic membranes.

The backing sheet mirror type was used in 1984 and 1985, and reported in references (3),(4),(5),(6) and (7), good reflected focussed images were obtained. The main fault with the two thin flat ring friction grip arrangement was that the rings slightly buckled under the bolt pull down forces. Ring buckling influenced the degree of friction grip on the membrane circumference, the membrane could be locally pulled out from between the buckled rings. The buckled rings also created non symmetries in the membrane tension, creating non symmetrical concave mirrors. Some twelve bolts were used to pull down the rings, the large number of bolt holes helped to reduce the stiffness of the rings. In most telescope mirrors the mirror can be pointed in any required direction by using three screws at 120° intervals. It was also noted that with this mirror when the mirrors pointed directly towards a target, they imaged better off axis than on axis. A clear indication that the membranes were not pulling down symmetrically. It was decided to use much thicker grip rings, cut down on the number of bolts to pull down the rings and pretension the membranes flat in the grip rings, before the rings were pulled down. It was hoped the stated alterations would ensure a more symmetrical concave shape and image symmetrically on the optical axis. It was decided to proceed in easy stages and evaluate the effects of each change.

d) <u>PRETENSIONED MEMBRANES, DOUBLE FLAT RINGS CIRCUMFERENTIAL GRIP</u>

In late 1985 simple membrane pre-tensioning techniques were established using rubber O rings and grooves combined with the two flat edge grip rigs. Figures 2 and 3 from reference (7), illustrate the technique. Figure 2 shows one ring with a shallow concentric groove into which a rubber O ring is lightly glued. The circular membrane is lightly gummed concentrically to the second ring. On bolting the two rings together the O ring pushes the membrane into the groove and pretensions the membrane into a tight flat surface. A less successful technique, again seen in Figure 2, was to use an O ring with a slit, the rings had grooves as before. The membrane circumference was slipped into the slit, which was then compressed to grip the membrane, by bolting the rings together. In practice it was found that the membrane could partially pull out from the O ring under large pressure differences . Figure 3 illustrates the final mirror. The main feature of this mirror was that the images of on axis objects appeared symmetrically on axis, the membranes were pulling down symmetrically.

e) <u>PRETENSIONED MEMBRANE, STRENGTHENED GRIP RINGS, THREE PULL DOWN BOLTS</u>

A pair of flat rings with concentric grooves were made. The top ring was thin and the bottom ring much thicker and stiffer than the examples in section (d). The rings were held together as before by small bolts,in order to pretension flat the membrane. Three large pull down bolts passed through the two rings, the bolts being at 120° to each other circumferentially around the rings. The bolts pulled the rings down over a specially designed and shaped central frame. Slight adjustment of the three bolt forces can move the rings at any angle with respect to the frame. Other novel features included a ring of separate small bolts screwed through the top ring, the bolts pressed down on to arcs of perspex lying over the pretensioning O ring. By adjustment of these small bolts the membrane circumferential force could be adjusted locally to achieve a fine tuning of the pretensioning. Since the unit is currently being patented by the University, only basic details can be released in this report. It was this mirror which the writer took for display to U.S.A.F. personnel in September 1986 and for simultaneous inspection by T.R.W. in Los Angeles. T.R.W. carried out an interferometric examination and stated that it was another large step forward in advancing the technology. The mirror can zoom instantly from the flat to f/0.5. The membrane has been flexed thousands of times and the aluminised skins show no signs of deterioration. The mirror has been left at f/0.5 for days under full stretch conditions, again the membrane showed no signs of creep or surface deterioration. The membrane was I.C.I. Mylar, aluminised by Kendall and Hyde, Aldershot, England. From displays of this mirror came the proposal to apply for a U.S.A.F. one year pilot contract of $15,000 to maintain the impetus of the research, to run fron January 1987 to January 1988. Unfortunately the money did not arrive until the first of June 1987, during which time the Pound collapsed against the Dollar and reduced the real money value in Pounds by some 30%. Such a large reduction meant sacrifices of money for purchasing materials etc. Despite the loss of money, several important contributions to active optics have been made, and will now be discussed.

f) U.S.A.F. CONTRACT JUNE 1987-JUNE 1988

The main thrust of the contract was to examine cast and rolled plastics in terms of roughness, consistency of stiffness across any one sample, break up of the metallised finishes under flexing. Also to study the utilisation of such plastics in actual flexible mirrors and compare if possible the various advantages and disadvantages of such materials. Were such mirrors capable of operation in partial or total vacuum, below an aircraft or in total space on spacecraft?

Research had commenced with the buying in 1986 of samples of cast polyimide plastic film in thicknesses up to 125 microns. Polyimide film was chosen because it was reputedly ultra-smooth and from the catalogues had yield strains ranging from 6 to 15 per cent. Samples of the film, together with samples of rolled plastic film, were sent to America for assessment of their roughness values. Figure 4 illustrates the results. The polyimide film in Figure 4a had an incredible roughness of about 10 Angstroms R.M.S which is about the limit for polished mirrors. Such a smoothness reduces light scatter to the absolute minimum. The polyimide sample of Figure 4b was 20 Angstroms R.M.S. The rolled plastics of Figures 4c and 4d were rougher, at up to 40 Angstroms R.M.S. Samples were measured with and without metallisation, there appeared to be little differences in the results.

Metallisation was by Kendal and Hyde at Aldershot, probably the best in England. At the suggestion of Dr A. Guenther, Chief Scientist, Kirtland A.F.B., New Mexico, contact was made with O.C.L.I. Coatings, Dumfermline, Scotland. A visit was made to inspect their premises and much enthusiasm was generated for future collaboration in flexible optics. O.C.L.I. possess a Zygo interferometer and are capable of examining the plastic substrates before and after metallisation. The Zygo can also be used to help tension the membranes flat to interferometric standards. However as the research continued other events were to overtake the 1987 O.C.L.I. collaboration proposals and leave this as a future option.

A decision was made to construct a flexible mirror which could be operated anywhere, in the atmosphere or if need be in outer space, termed a space mirror.

Figure 5 illustrates a schematic of the finalised mirror. The metallised mirror lies at one end of a tube, the other end of the tube is blocked by a flat sheet of pretensioned super smooth, clear thin plastic. The first prototype, just completed, was successfully demonstrated to Dr Guenther at Glasgow in late June 1987. From Figure 5 it can be seen the concave mirror can be operated in various ways. Air under pressure can be introduced into the tube body, forcing back the metallised mirror into a concave shape. Or a vacuum can be used behind the metallised sheet, with air in front of the metallised sheet. The air either being at or above atmospheric pressure in order to force the mirror back. A third technique would be to use two vacuums, one on either side of the metallised sheet, with the higher vacuum behind the sheet. The two vacuum system would be suitable for space since the thin flat clear plastic sheet over the tube end would scarcely bulge, having a total vacuum outside and a partial vacuum inside. Having a vacuum in the tube would also help prevent air expansion or contraction in the tube, with variation of tube temperature. Thermal currents are thus minimised in the tube, which would cause a shimmering of the image. A 20 micron thick clear polyimide sheet, of yield strain 5%, was used to seal the tube end. The main mirror was 125 micron thick metallised polyimide of 15% yield strain. The clear sheet was pretensioned into a very tightly stretched stiff flat surface, using a pair of flat rings, grooves and an O ring. The flat surface could not be seen to flex in operation, even with the softer metallised mirror operating at f/0.5. The tube length was such that the target light which entered through the clear plastic and reflected from the metallised sheet, focussed and imaged back outside the clear sheet. Such a system was deliberately chosen since it was now possible to place any associated phase conjugate optics outside the tube. Rays reflecting from the concave focussing mirror can be focussed into a phase conjugate medium. From this medium the light rays retroreflect and retrace their exact paths back through the system. Such a technique cancels out all the aberrations of the mirror system. In the space mirror the target light rays would pass through the clear plastic and travel down the tube to reflect from the concave mirror to retroreflect from the phase conjugate medium outside the tube, passing back through the entire tube optical assembly. All errors and aberrations are cancelled out for the entire space mirror system.

Figures 6a and 6b illustrate front and rear views of the space mirror, while 6c illustrates an image of a standard U.S.A.F. test chart image. All the lines were visible with a metallised mirror of eight inches diameter, stopped down to five inches aperture. The field of view was 5 degrees, which presented severe spherical aberration and coma, hence the necessity of stopping down the aperture to increase the f/no. For Figure 6c, the final f/no was f/2.0.

However problems soon arose when it was noticed that after several weeks the image resolution had significantly decreased, something that had never happened before when using the rolled plastics. Visual examination of the flexed metallised polyimide mirror revealed that it was not maintaining its uniformity of stretch. Some areas had reduced in stiffness and appeared to be bulging to different degrees under the pressure difference. What was required was an interferometer, in order to visually examine in real time any changes that were occuring.

During a previous visit in early 1986, to the National Physical Laboratory, Optical Metrology section, London, attempts had been made to use a ZYGO interferometer to examine the surface of a flat and flexed mirror of type (d). The test results are illustrated in reference (1). The ZYGO, as with the vast majority of interferometers, is only capable of examining spherical or parabolic shapes, by comparing the actual surface against a series of different master spheres of varying f/nos. If an aspherical test mirror is used, then only those parts of the mirror with the same curvature as the master will appear covered in fringes on a viewing T.V. screen. In general with an aspheric mirror only a small part of the mirror central region is seen, plus a thin slice across the test mirror, a slice whose curvature was equal to that of the master reference. Enough fringes were seen to show that the two thin flat membrane grip rings were flexing in a cyclical manner, following the pattern of the pull down bolts through the rings. The same cyclic ripple was seen interferometrically in the actual concave mirror,this is a non correctable aberration. From this information came the design described in (e), the rings were stiffened up and were kept flat at all times. A laborious investigation of interferometers lead to the evolvement at Strathclyde University of a variable shear, radial shear, interferometer, reference (1). and by 1987 a lateral shear interferometer was operating.

Figure 7 schematically illustrates the lateral shear interferometer. A laser beam was focussed through a pinhole to expand out and produce a clean beam, the beam opening out at the focus of a flexible mirror, to reflect back from the mirror as a collimated beam. The reflected collimated beam strikes an optically flat plate. One beam reflects from the plate front surface, while a second beam, is transmitted through the glass to reflect from the optically flat back face of the plate. The two beams now interfere with each other, the interference pattern appears on a screen. If a perfect plate is used, optically flat front and back, plus being of uniform thickness, and one also has a perfectly symmetrical flexible mirror, then straight parallel, equally spaced fringes are seen on the screen. If the plate is not perfect, or the mirror not symmetrical, then the fringes are distorted. Obviously a perfect plate is desirable, leaving any distortion on the fringes to have been caused by the mirror only.

The quality of the plate can be checked by using a point source of laser light opened out normal to the plate surface, i.e. a spherical wavefront. Front and back reflection of the beam now occurs, the two beams interfere. For two spherical interfering wavefronts, a series of concentric rings are seen for a perfect plate. Figure 8a illustrates a very good plate as evolved and used at Strathclyde. Figure 8b illustrates a poor quality plate. Reference (16) illustrates a lateral shearing interferometer plate. Further references illustrate how specialised small sized lateral shearing interferometers can examine much larger sized concave mirrors, references (17) and (18). One does not need a large, very expensive optically flat splitter plate, as large as the mirror being examined.

Test results from the flexible mirrors are illustrated. Figure 9a, illustrates a typical pattern for the soft 15% yield strain polyimide film. The large semi-circular black zones at the mirror circumference, are caused by dirt particles between the membrane and the central stretch frame. The dirt particles cause large localised stress and strain concentrations which spread right across the mirror. At great trouble throughout 1987/88 a dust free room was built at Strathclyde University, Mechanical Engineering Group. The mirrors are now constructed in this room. Figu 9b illustrates a lightweight tube leaning against the mirror centre. Figure 9c illustrates the interference pattern around the top of the tube. The system is very sensitive, even extremely small creases on the metallised skin, barely perceptible to the eye, scatter the reflected collimated beam to such an extent that the crease areas appear as dark regions having no fringes. It was discovered that the mirrors became more symmetrical as the curvature increased or the f/no decreased, i.e. the fringes became more parallel and straight, limited of course by dirt particles behind the membrane. The only logical conclusion was that the mirrors were more non symmetrical in the shallow curvatures, because the pretensioning system of an O ring and concentric grooves was less than optically or interferometrically accurate. The surface was not 100% uniform in flatness and pretension. For shallow curvatures the tension forces are not much greater than the pretensioning forces. Much thought was addressed to the problem and completely different pretensioning techniques have been adopted. Experiments are currently under way, involving temperature shrinkage of biaxially stretched rolled plastics, combined with a final adjustment over a stretching frame. New superb quality metallised rolled plastics are being used. Quite remarkable improvements in image quality have already been obtained. The University is currently awaiting further test results before deciding on the form of patenting. Figures 10a,b and c from reference (9) illustrate the mirror becoming more symmetrical as the curvature increases. The new interferometer also rapidly established that extremely good vibration damping of the flexible mirrors was being achieved. Very large drive forces were needed to establish resonance on the skins, reference (8). Along any one radius of a curved flexible mirror there is a large variation of resultant stress. The local resonance is directly related to the local resultant stress. Hence along any one radius there is a large variation of frequency. Such a system makes it extremely unlikely that the film fundamental frequency can be excited, that is the mirror centre has the maximum amplitude. Obviously if the mirror vibrates in a fundamental frequency then the reflected images would be distorted. Using the interferometer it was seen that the mirror damped out any vibrations literally instantaneously. T.R.W have confirmed similar findings to the report writer.

The final testing of the flexible mirror was involved with their use in white light holography, using both transmissive and reflective holographic arrangements. In transmission holography the laser beam is split into two beams. One beam reflects off the test object and is called the object beam, this lands on an unexposed hologram photographic plate. The other part of the split beam is called a reference beam, and this lands directly on the same side of the plate. The angle between the beams is typically 20 to 30 . The two beams of coherent light interfere with each other, the spacing of the fringes gets closer as the angle between the beams increases. The plate emulsion records the interference pattern. The plate is developed and fixed, possibly even bleached. The image of the test object is seen in 3D when a conjugate reference laser beam is introduced on the opposite side of the plate from where the object reflected beam had been. The interference pattern acts as a diffraction grating and diffracts or bends the light rays to refocus in space and create a 3D image. In reflection holography the reference and object beams are arranged to land on opposite sides of the unexposed photographic plate. The fringes are now very close together since the angle between the beams can now be almost 180°, the beams are almost parallel. The smallest disturbance in the optical system will now move or blur the interference fringes being recorded in the emulsion, no hologram is recorded. Some indication of the quality of the mirror curvature stability with time is that excellent holograms were taken with short wavelength green light Argon lasers. Fringe spacing is also proportional to wavelength. In green light the fringes are closer together than is the case using Helium Neon laser red light. Green exposures of ten seconds were not uncommon, giving excellent images, reference (12). Holograms to one metre by one metre were taken, much larger is perfectly feasible. Larger flexible mirrors i.e. several metres in diameter are required, if larger white light holography is being undertaken. White light holography can be of different types, but usually involves making holograms of holograms. The final hologram can be replayed with white light and the various colours of the spectrum can be chosen, each colour appearing individually or collectively.

In a S.D.I. participation handbook for British companies, Pilkington-Perkin Elmer, St Asaph, Wales were seen to be involved in key technology for SDI. Use is being made of solid concave spherical mirrors and the making of lightweight hologram equivalents of those mirrors, reference (13). Reflection holograms are made of solid concave mirrors by placing a flat holographic plate or film over the front of a solid concave mirror. A laser beam is expanded to strike the film, this is the reference beam. Some of the beam goes through the film, reflects from the concave spherical mirror and again strikes the plate, this is the object beam. Obviously if very large diameter concave mirrors are being used, very large holograms of large aperture can be made. However hologram plates are limited to around one metre by one metre in size. Holographic film can be several metres across and up to ten metres long. Larger sizes could be arranged. The report writer gained invaluable experience in the use of holographic film of extremely fine quality (Agfa Gevaert and Ilford). The hologram now takes the place of the mirror and can be used to focus laser beams etc. If a white light hologram of this hologram is now made, then a wavelength selective hologram mirror can be created, used in head up displays, SDI research etc. The Strathclyde mirrors could possibly be used to create very large hologram mirrors, with a large range of curvatures.

Finally a mention is made of a superb microscopic system used by the report writer, for examining in detail the surfaces of the plastics, metallised or not metallised. A graticule scale gives an indication of the size of the particles found on the metallised surfaces. Figure 11a illustrates the superimposed image of the graticule and an image of a sample of metallised rolled plastic film, used as late as early 1986. Individual particles are seen all over the plastic, a very rough finish. An image from newly discovered (1988) biaxially stretched rolled and metallised plastic, as currently used at Strathclyde, is seen in Figure 11b. The material is so smooth that the particles cannot be seen, even on the highest magnifications, being so much smoother results in superb imaging.

## CONCLUSIONS

In the year of the report, 1st June 1987 to 1st June 1988, large and important developments have occured in the evolution and use of stretchable concave imaging mirrors.

A study has been made of cast and rolled plastics, including biaxially stretched rolled plastics. A great deal of time and money was wasted in procuring samples of Japanese polyimide cast plastics, via London. Although these plastics were indeed supersmooth to around 10A , the samples were found to suffer from variations in stiffness. It may be that the metallising specialists Kendall and Hyde had no experience with polyimide film. Their metallisation of ICI rolled Mylar was superb, but with polyimides there was evidence of metallisation tear drop effects. It appears that metallisation of polyimides is a specialist task. The writer knows one San Francisco researcher, specialising in metallised polyimides, who wanted $10,000 for one roll of the metallised plastic! Unquestionably the polyimides show great promise and it would be unfair to dismiss them out of hand on the basis of the experiences obtained during this report. Using a powerful microscope with a superimposed graticule image, the surface structure of the unmetallised and metallised plastics could be readily examined and measured. No evidence was noticed of any significant break up of the metallised layers on any of the plastics, the mirrors operated repeatedly to f/0.5 or approximately 5% strain. However the experiments were in laboratories. The effects of humidity, bright sunshine, high and low temperatures, would have to be studied accurately in a longer test programme. At the time of writing this report a roll of the finest mirror finish metallised, biaxially stretched rolled plastic yet discovered has been obtained. The rolls are 1.2 metres wide, 30 metres long at $320 a roll, material thicknesses to 250 micron. Tests indicate that the material is by far the best to date, greatly superior to the ICI rolled Mylar, metallised by Kendall and Hyde and also far cheaper. Being biaxially stretched the new material responds to low temperature shrinkage (85 C) and is eminently suitable for accurately pretensioning flat by heat shrinkage.

The mirror designs have improved considerably, mainly due to the ability of being able to interferometrically visualise the symmetry of the mirrors. The O ring and groove technique worked quite well for pretensioning, but is not accurate enough for very high resolution imaging. A completely new mirror using a radically different system of pretensioning without heat shrinkage was designed, built and tested in late 1987 and works extremely well. Examination of this mirror by the interferometer indicated that slight improvements could still be realised. Currently these improvements are underway and will involve membrane heat shrinkage coupled to the new pretensioning system. The membranes will be pretensioned and then shrunk by heating. The final mirrors will still have a stretch frame, required as a vacuum seal, and also helping to achieve 100% uniform tensioning. Tests on heat shrunk only mirrors indicate that optical magnifications of x65 could be used without deterioration of image quality. The mirror was a membrane disc, heat shrunk onto an accurately made ring of material. No pretensioning of the membrane was used before heat shrinkage, no stretch frame was used and heat shrinkage was by blowing hot air from a hair dryer!! Since magnifications to x400 are not uncommon in telescopes, the Strathclyde mirrors have a way to go. Comparative tests were made with the Strathclyde mirror and a polished silvered parabolic mirror of similar f/nos, laid side by side and imaging the same target. Figure 12a illustrates the two mirrors and figure 12b illustrates the two images side by side, the flexible mirror was a type (e).

It should be possible to create small sized flexible convex secondary mirrors in order to cancel out aberrations in a larger flexible primary concave mirror. Such techniques have been partially examined and the results are encouraging.

Development of the interferometric examination of the mirrors is desirable, not only from a symmetry view point but also establishing image resolution values. A small new styled lateral shearing interferometer will be built, in order to examine much larger sized flexible mirrors.

The combination of holography with the mirrors appears to offer attractive experimental work for the future. Replacing heavy polished monolithic or segmented mirrors with lightweight holograms of those mirrors must be an attractive proposition for space applications. If a collimated laser beam is combined with a point source spherical beam in a reflection hologram, a parabolic mirror hologram can be achieved, reference (19). However if a very large aperture hologram mirror is required, then a very large collimated laser beam is needed, necessitating a large collimated mirror or lens. Such a mirror could well be the Strathclyde mirror. Mention has already been made of the Pilkington research into hologram mirrors for SDI and head up displays. Holography itself can be used as an instrument for the testing of large aperture optics, reference (20). If a hologram is made of the wavefront emerging from a lens (or a mirror) then the hologram, when used in combination with the lens or mirror, serves as a corrector plate for that lens or mirror, reference (21). Holographic lenses can be used to create variable lateral shear interferometers, reference (22).

Attempts have been made in the past to construct extremely thin, light, large aperture, monolithic mirrors. The problem is that the mirrors have to be very accurately supported and to the best of the writers knowledge have only obtained infra-red quality to date, reference (23). The Large Deployable Reflector (LDR) is a 20 metre diameter Cassegranian system with actively controlled segments, diffraction limited to infra-red wavelengths 30 to 50 microns and used in space. The segment sizes are such that they can be lifted in the Shuttle and assembled in space, reference (24). However such systems can also be used as interferometers or phased telescopes for target beam shaping or image processing in the optical, infra-red and submillimetric spectrum regions, reference (25). Such a system is obviously not cheap! Image resolution depends essentially on two parameters, size and shape of aperture and wavelength used, The largest possible apertures are necessary for the wavelength being observed, in order to attain maximum resolution. However if targets are observed through the earths atmosphere the target light suffers phase and amplitude distortions in passing through the air, the image is distorted. Use is made of active optics, usually a flat mirror membrane to remove the distortions. The target light is passed from the concave main imaging mirror of the telescope through an interferometer which senses the phase distortion of the target light. The distortion information is passed to a series of control units behind the membrane, which suitably distort the membrane in order to restore the phase lost in passing through the atmosphere. The target image is now suitably sharpened and resolution is regained. Two such systems, one monolithic and one an array, are described in references (26) and (27). An extremely interesting active concave plasic membrane mirror is that described by Mihora, reference (28). A concave charged plate of one radius of curvature is placed behind a thin metallised plastic membrane. The charged plate is actually an array of voltage control segments. The membrane is drawn back into a reasonably accurate concave shape, different areas of the membrane can be suitably readjusted in shape by a voltage change at that area. The report was written in 1980 and at that time the unit was only capable of infra-red image quality. Drawbacks to such systems in general include the necessary use of very large voltages in order to force the skin back into a deep concave shape of small f/no. A 4.88 metre, f/4.5 model was described, a very shallow curvature. The normal electrostatically displaced membrane mirror is suitable for one curvature only, since the distribution of the voltage control elements dictates that curvature. One would need literally millions of voltage control elements to achieve optical imaging accuracy. Mention was made of experiments in the 1960's on membrane mirrors made of MYLAR, obtaining infra-red quality. Mention was also made of pneumatic and electrostatic forming of membranes for millimetric wave surface quality, on mirrors to one metre in diameter. It would therefore appear that the writers mirror, in publications, was the first to achieve optical wavelength imaging.

Competition to the writers mirror is currently appearing, although the competition does not yet appear to have managed to obtain optical images. A Japanese paper describes a LIDAR (Light radar) concave membrane system in which the writer of this U.S.A.F. report, Dr P. Waddell, is mentioned, reference (29). A Norwegian paper describes a concave metallised membrane mirror used as a variable optical time delay, again the writer of this report is mentioned in acknowledgements, reference (30). Most significantly the Russians are apparently expressing an interest in the writers research, not to the report writer directly, but indirectly through others in London, Sunday Telegraph newspaper article, reference (31). It is well known that the Soviets propose making gigantic space mirrors for large lasers in space. Unquestionably these lasers will have wartime applications i.e. the use of powerful space lasers combined with phase conjugate optics and large antennae for automatically tracking targets, including underwater submarines. The automatic tracking of targets by phase conjugate optics is described in reference (14). As radar goes down into the infra-red, Terahertz technology, for discrimination between active and dummy warheads by examination of their heat wakes, there is a need for large aperture, optically accurate, concave antennae. Terahertz technology is described in reference (32).

The writers variable curvature concave mirrors appear to fill a niche in antennae technology. Variable curvature mirrors of optical imaging accuracy are important, with and without, superimposed electrical distortion controls, to reshape the mirror with extremely small voltage arrays. The mirrors have other important uses in holography etc.

The writer wishes to sincerely thank the U.S.A.F. for supporting this particular project. The test programme remit had to be curtailed due to the loss of funds as

described previously. It is obvious that the mirrors are still capable of development, both in the plastic materials and the frame designs. The writer would like to visit various people in Europe, USA and Japan, all involved in membrane mirror and plastic technology, for cross breeding of relevant ideas. The writer would like to continue the reported line of research in a longer term contract with the U.S.A.F.

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Principles of construction of mirror using a circular, ultra-thin, metallised plastics film stretched over a specially shaped frame. The circumference of the skin is gripped between two flat clamping rings, which are then pulled down over a central stretching frame. By changing the pressure across the film it can be turned into a concave or convex mirror, with focal length remote-controlled at will.

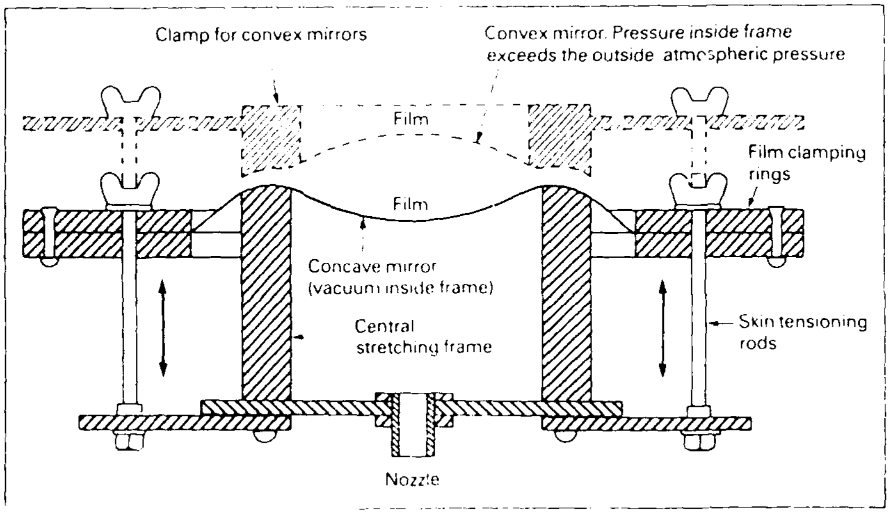
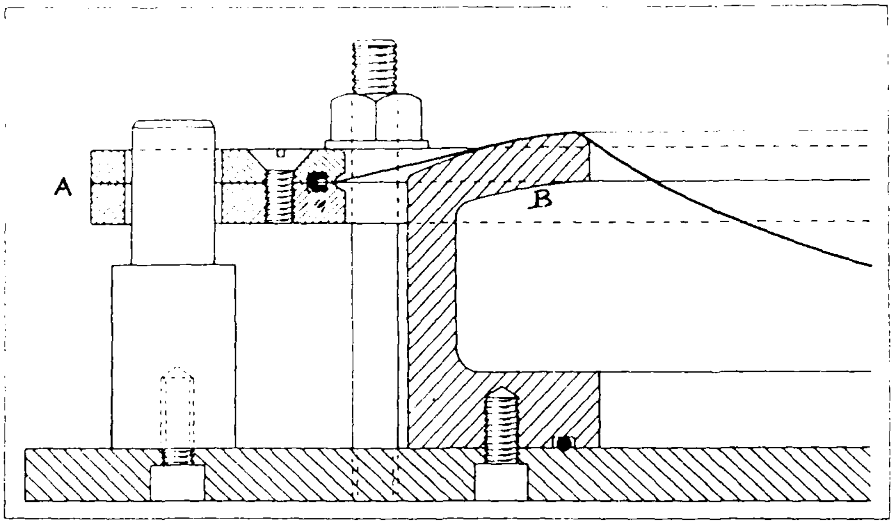
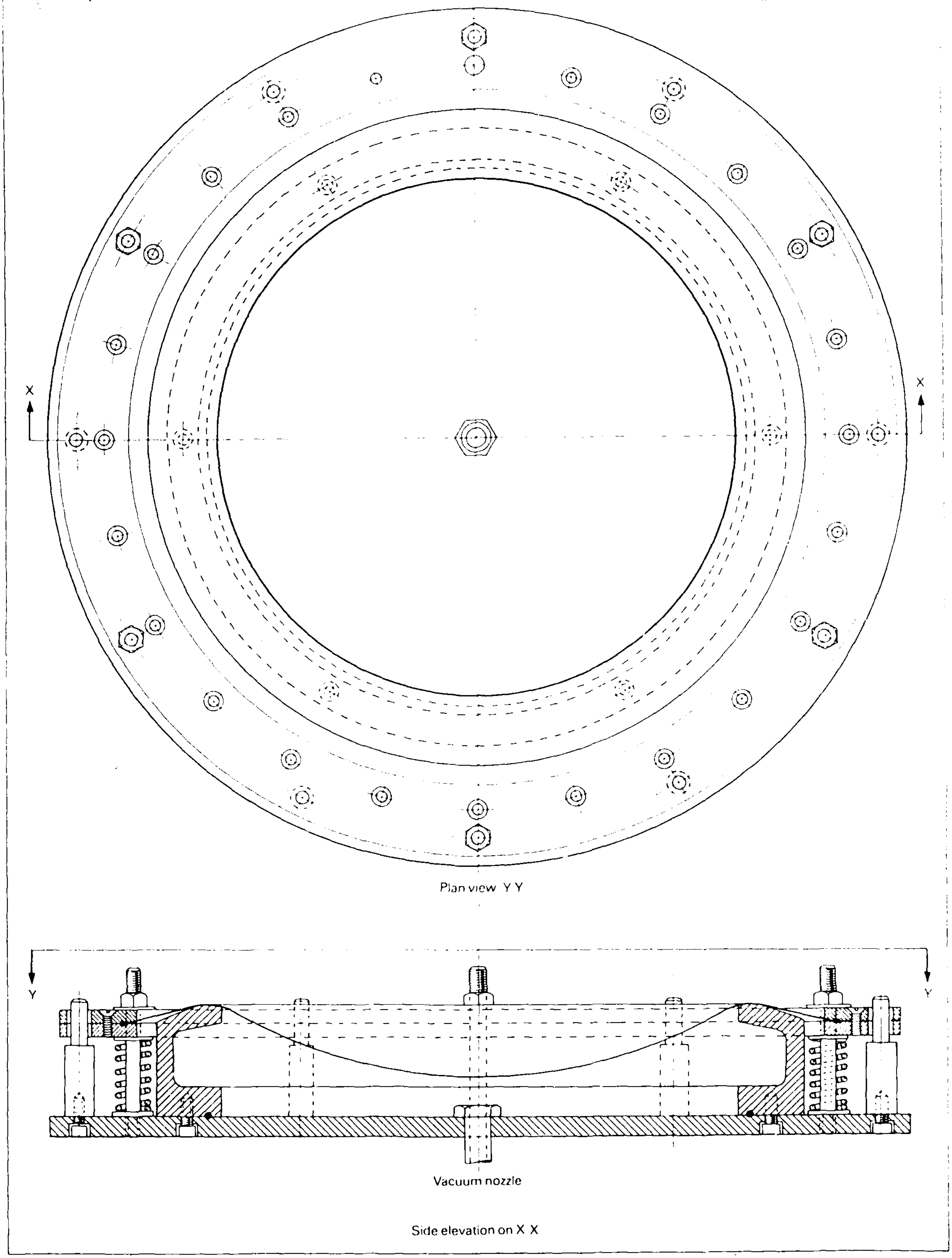



FIG. 1




Alternative edge grip in which a rubber bead grips the film edge and is squeezed tightly over it.

FIG. 2




General arrangement with the bead grip. A very small vacuum introduced behind the film causes it to be pushed into a concave mirror shape.

FIG. 3

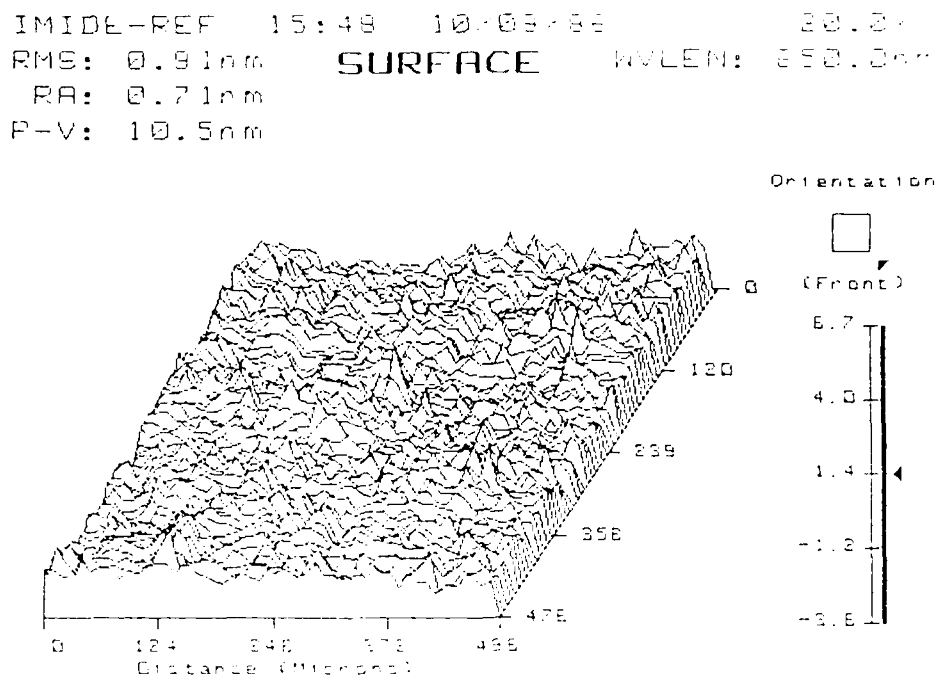



FIG. 4a POLYIMIDE

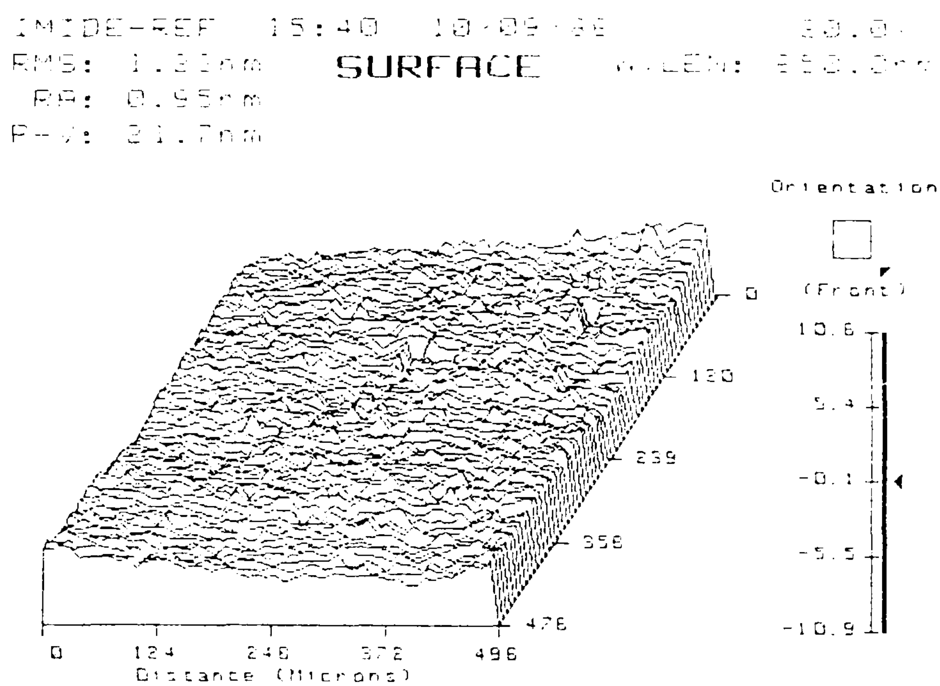



FIG. 4b POLYIMIDE

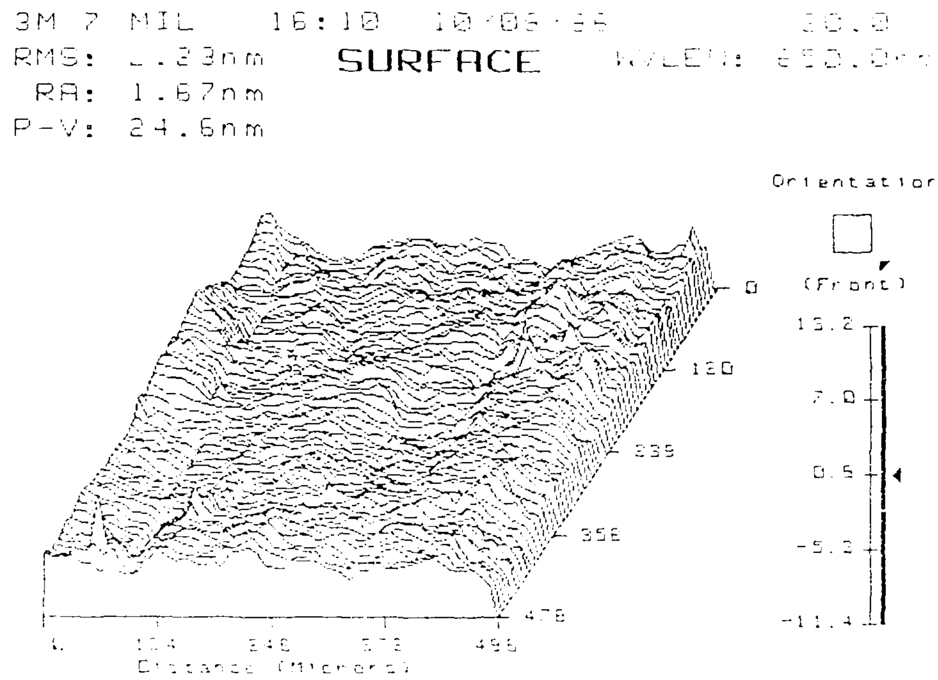



FIG. 4c 3M. MATERIAL, 7 MIL THICK (175μ)

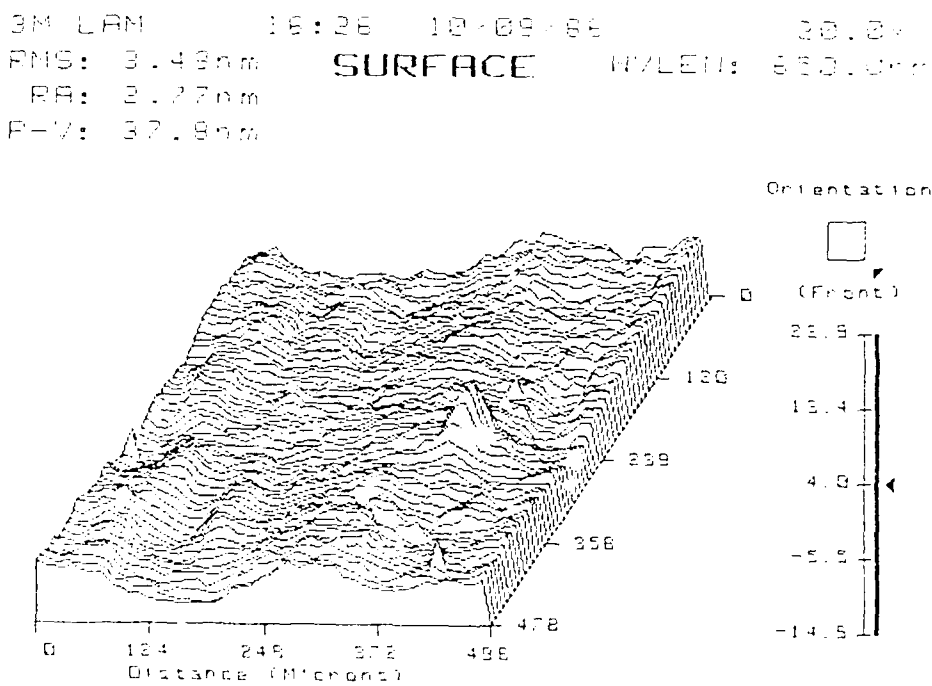
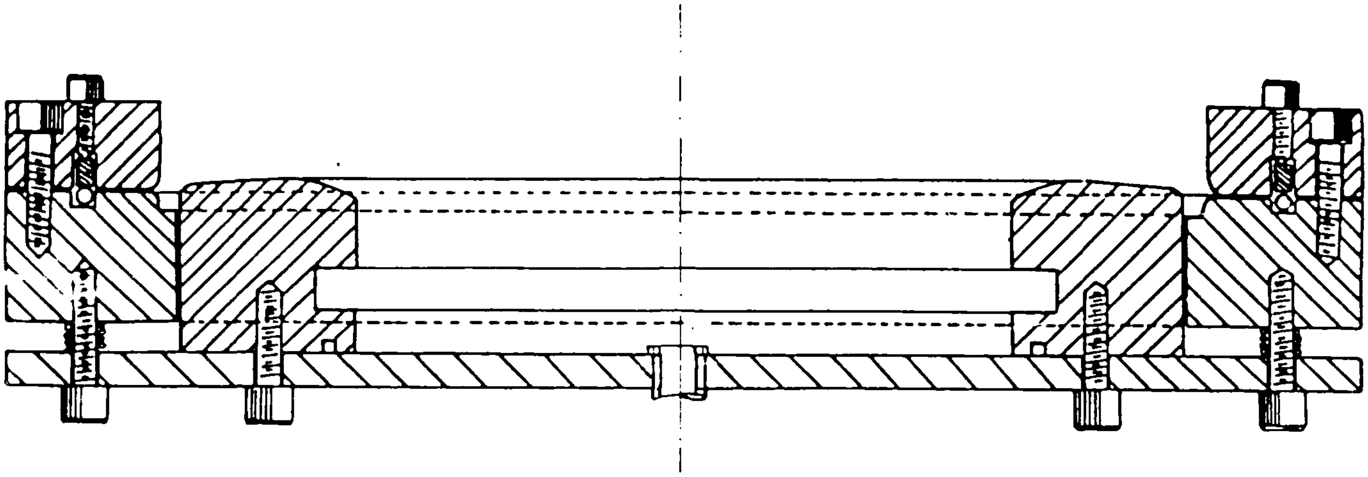
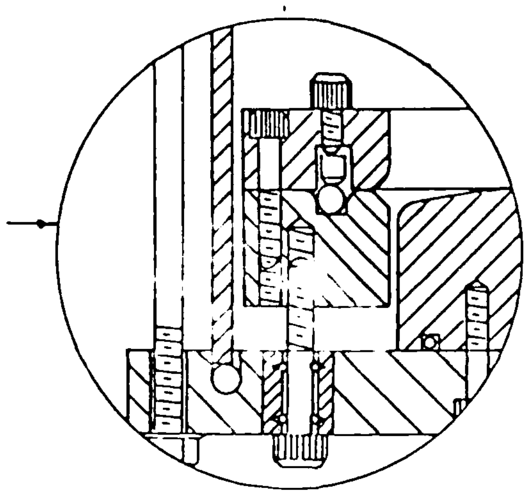



FIG. 4d 3M. LAMINATED MATERIAL



CONCAVE MIRROR ARRGT



SPACE MIRROR

ALTERNATIVE ARRGT

3 Adjustment Screws Come Out Through Base of Cylinder, Using Vacuum Sealed Screws.

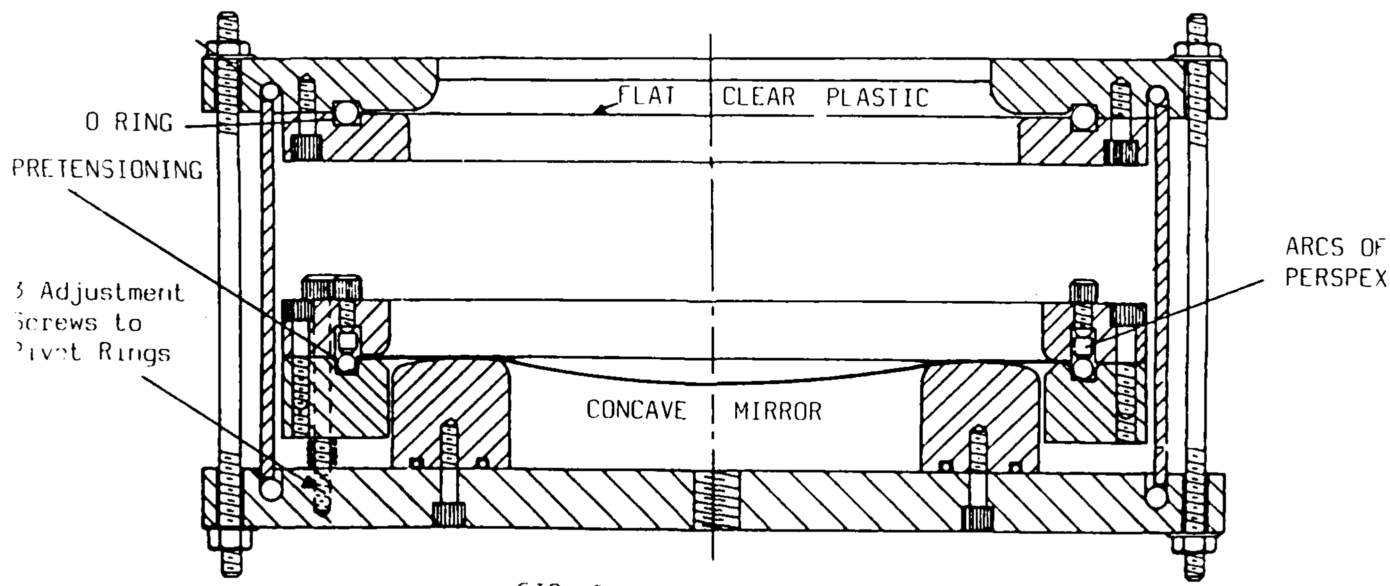



FIG. 5 SPACE MIRROR

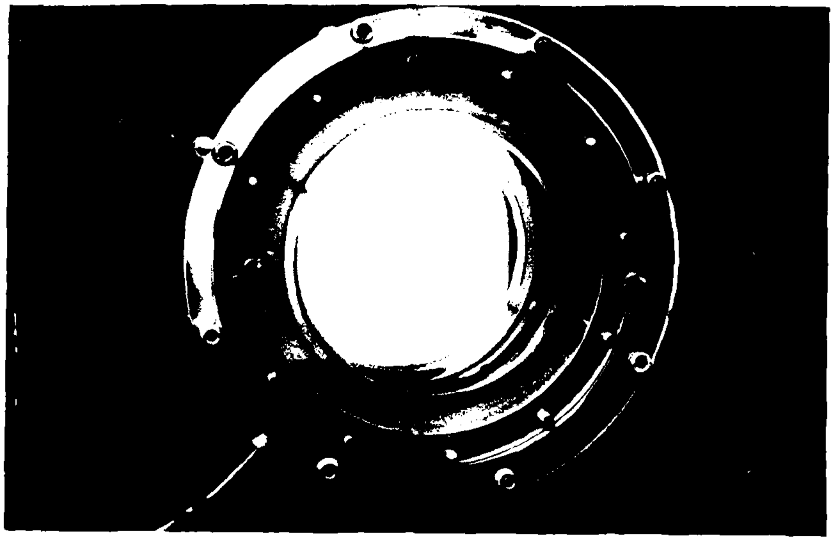


FIG. 6a

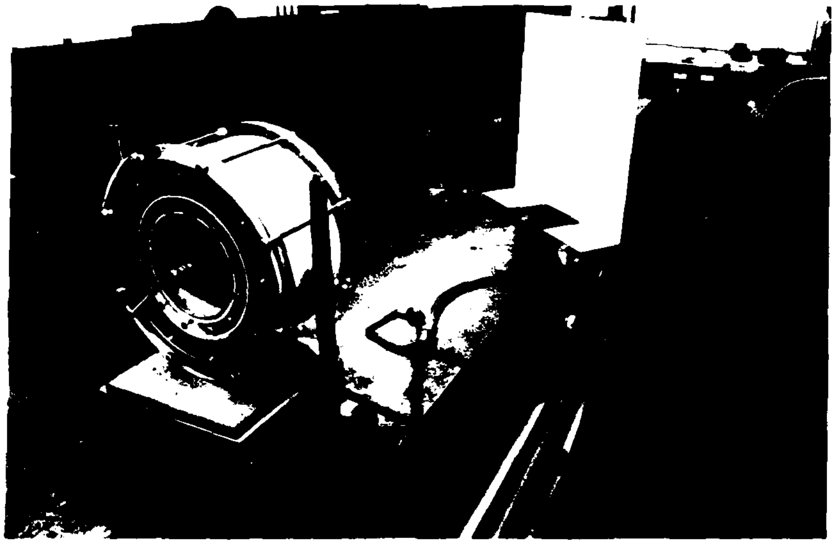


FIG. 6b

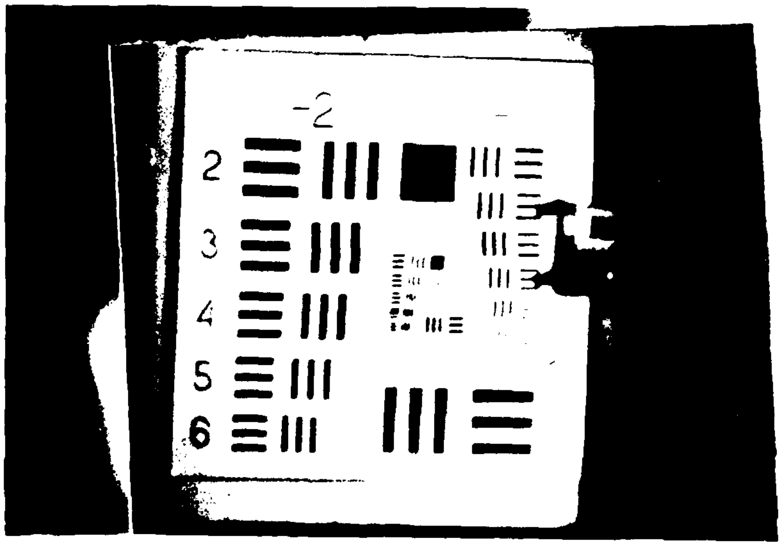



FIG. 6c

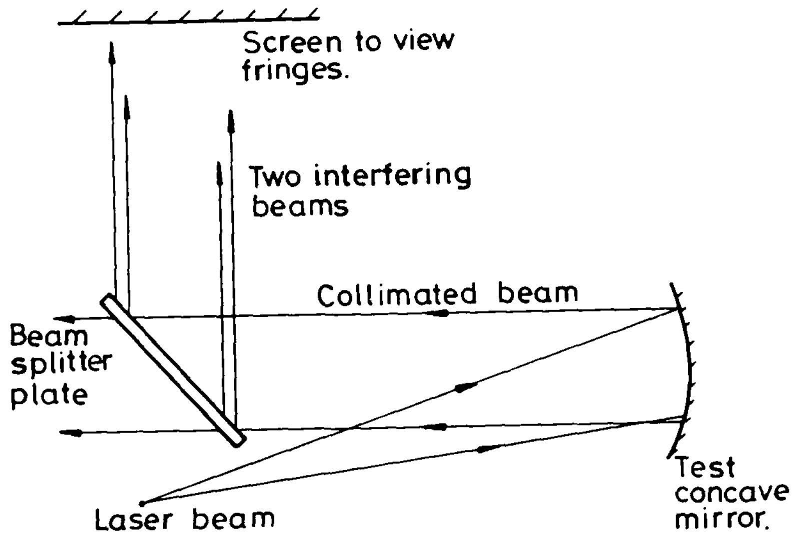



FIG. 7

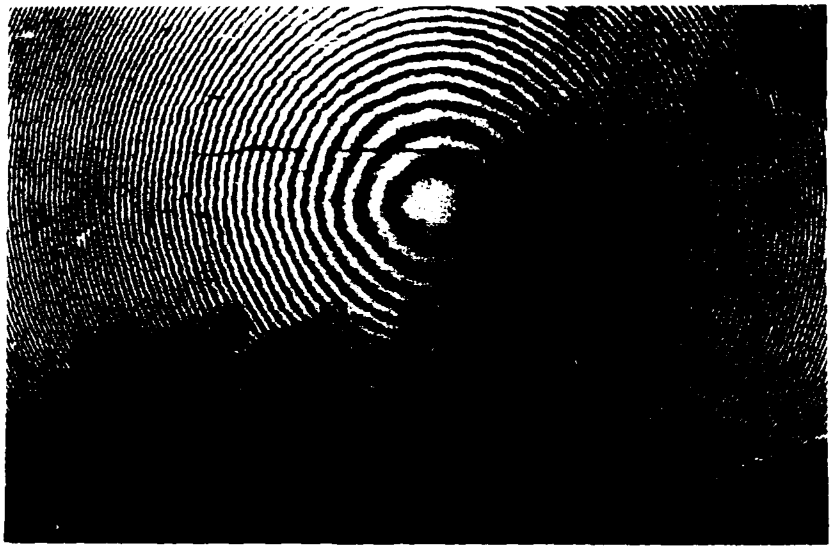


FIG. 8

FIG. 8b

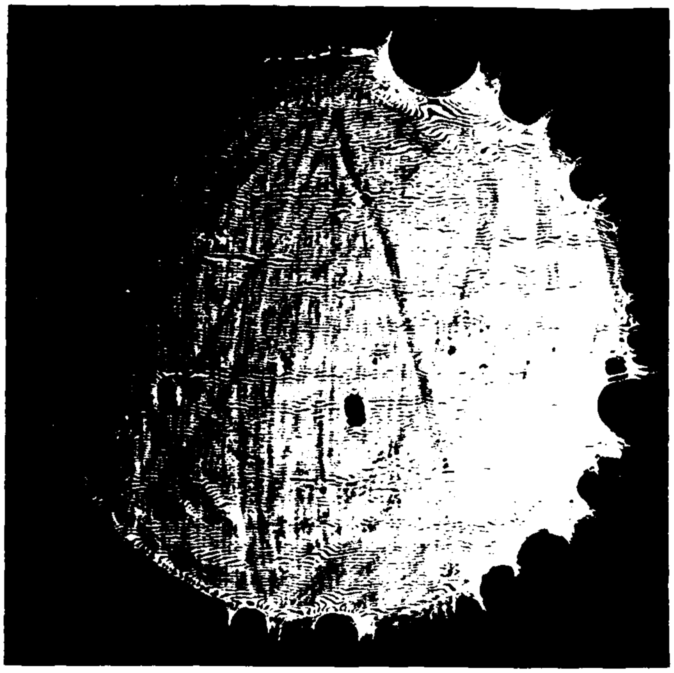


FIG. 9a

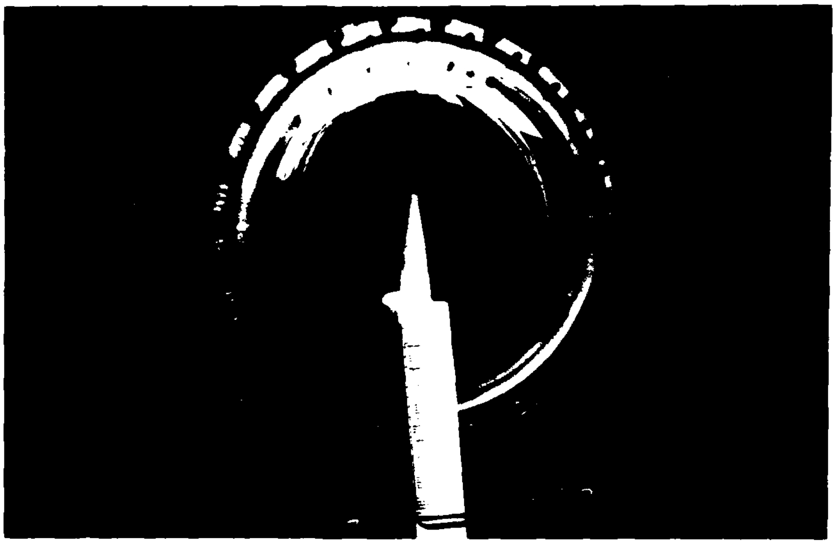


FIG. 9b

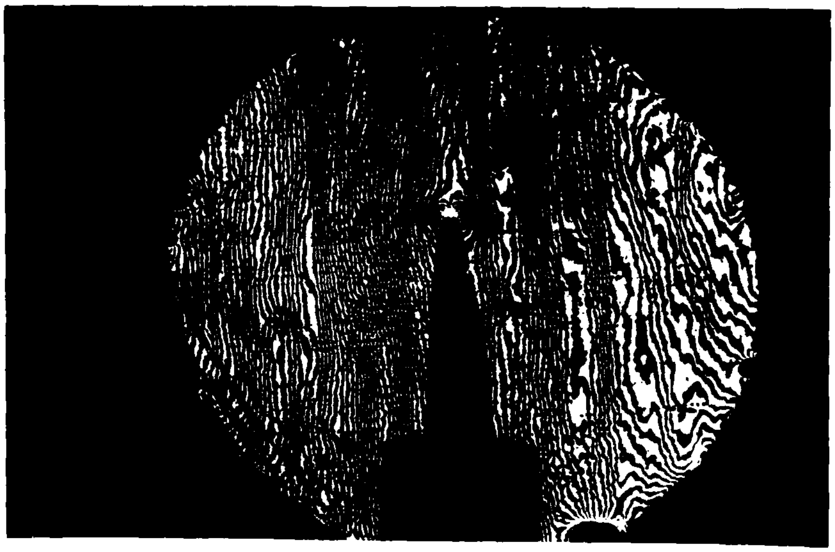


FIG. 9c

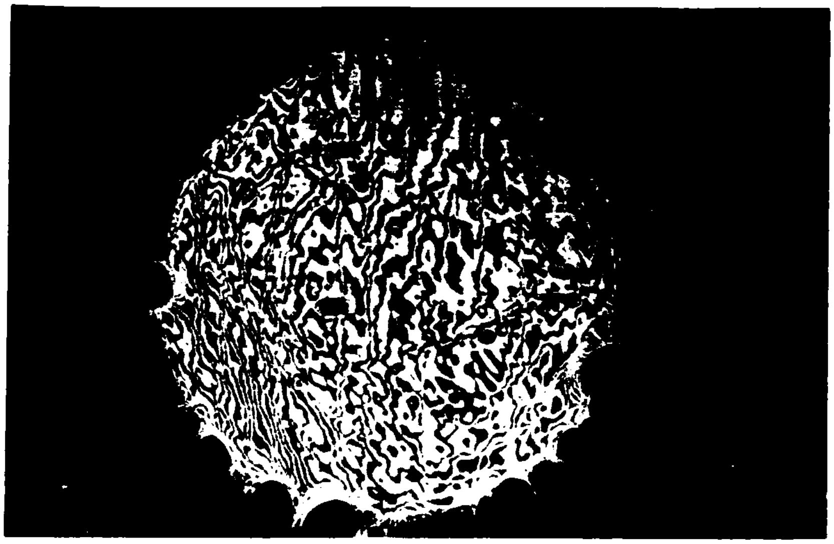
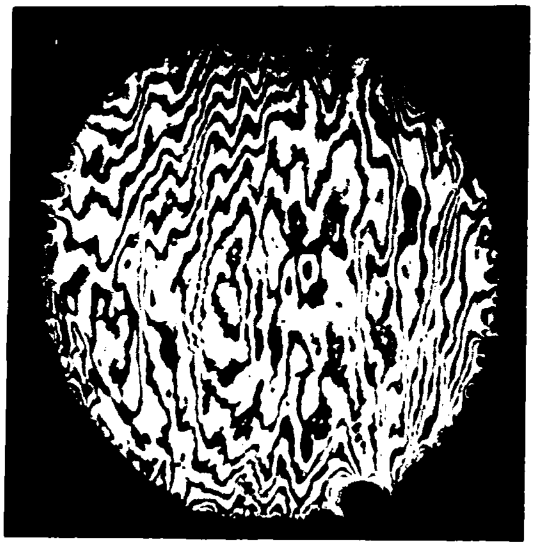


FIG. 10a



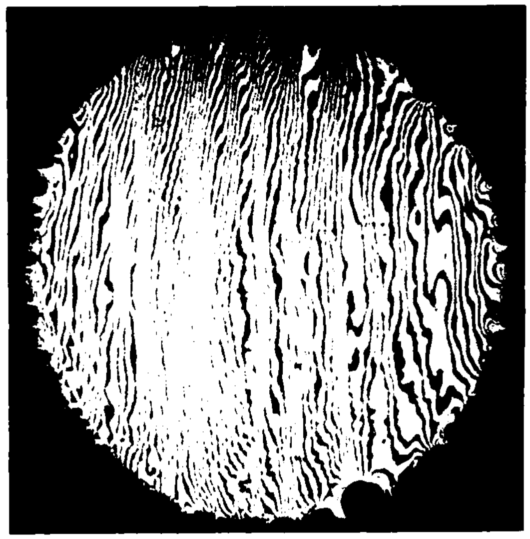


FIG. 10b

FIG. 10c

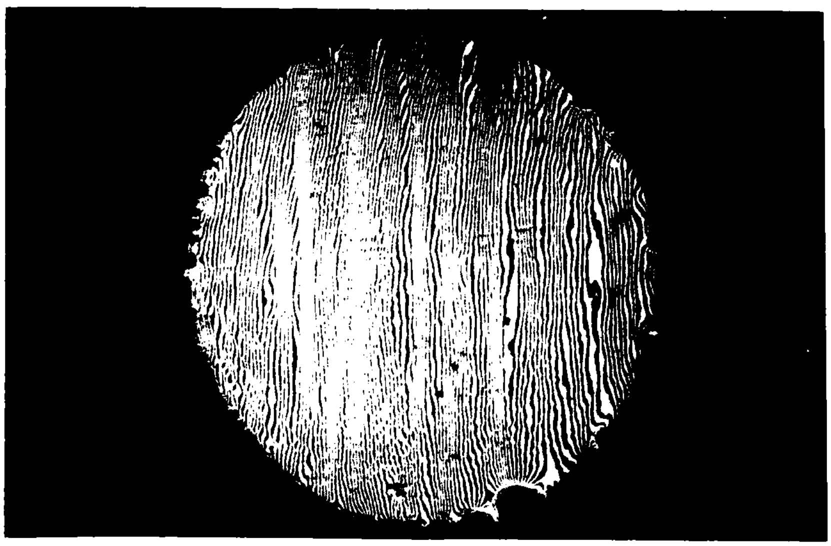


FIG. 10d

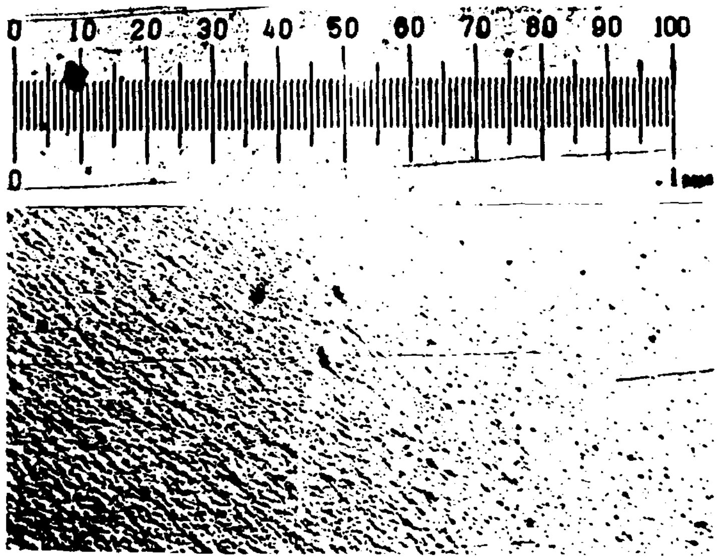
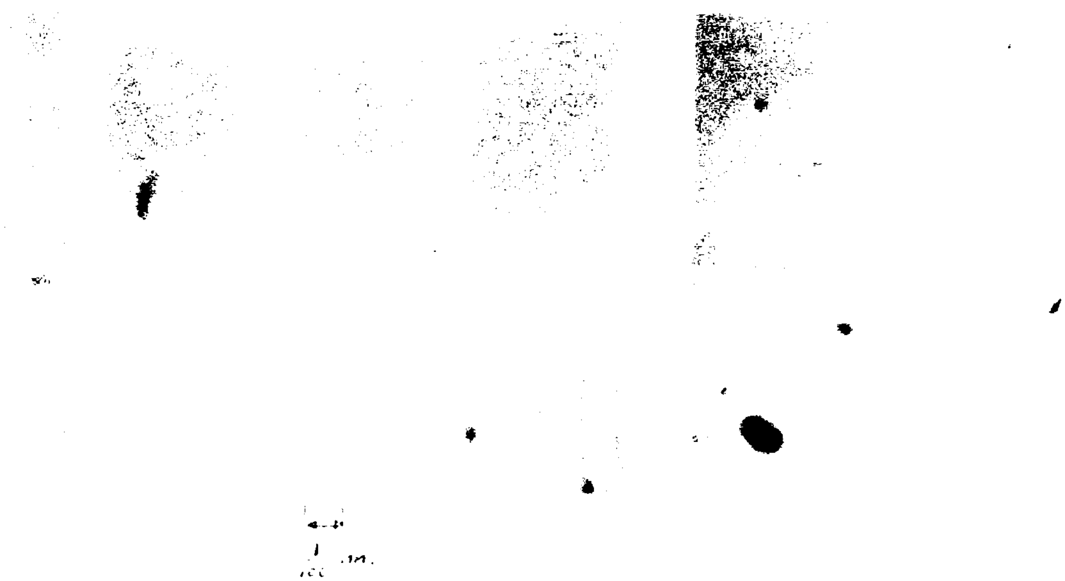



FIG. 11a

IMAGES

TO SAME SCALE



IMAGES TO SAME SCALE

FIG. 11b

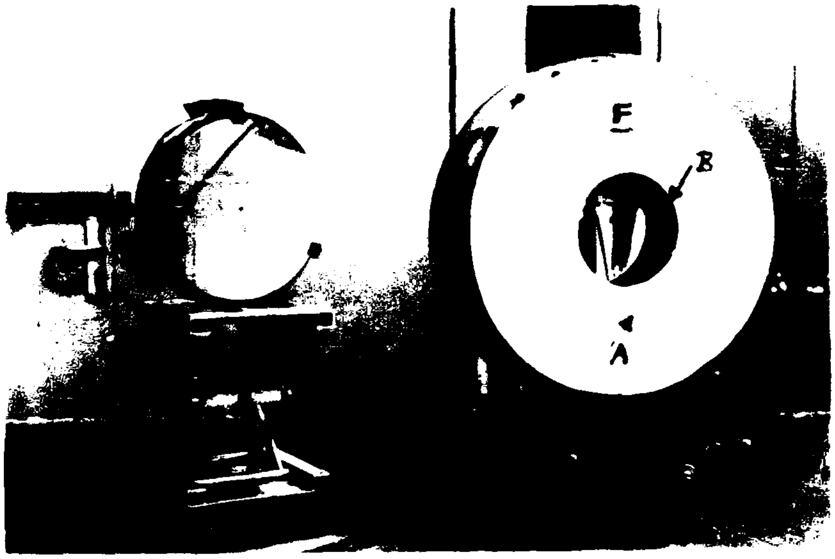
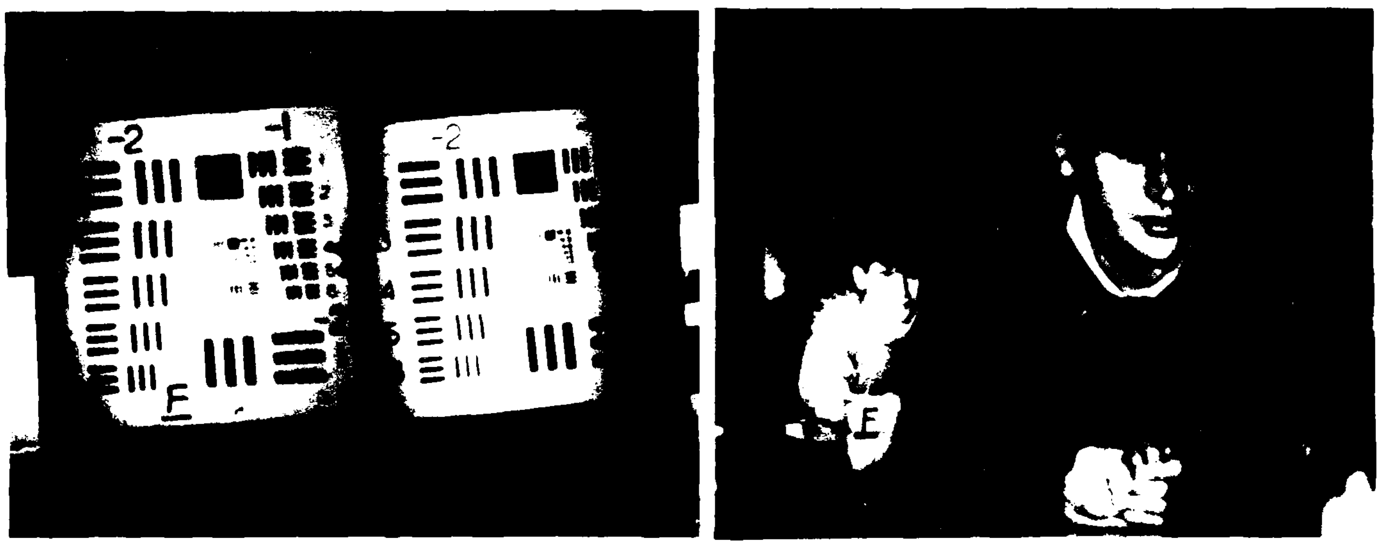



FIG. 12a




MIRROR 'F', STOPPED DOWN TO GIVE
SAME SIZED IMAGES i.e. SAME
F Nos. APERTURE SIZE 'A' USED.
IN OTHER PHOTOGRAPHS, SIZE B USED. FIG. 12b

FIG. 12b

COLOUR PHOTOGRAPHS.

TWO MIRRORS AT DIFFERENT F. No. IMAGES SIDE BY SIDE ON SCREEN.